Electron Beam Propagation in Magnetic Fields

S. G. Walton, C. D. Cothran, and W. E. Amatucci

***Abstract*—Cold cathode plasma electron beam sources are robust alternatives to hot filaments and field emission sources. In applications requiring pressures above 1 mtorr or reactive gas backgrounds, cold cathode plasma sources can produce high-power electron beams while also exhibiting long lifetimes. The images presented here are produced by electron beams extracted from cold cathode plasmas.**

***Index Terms*—Electron guns, magnetic fields, plasma sources.**

ELECTRON BEAMS are used in a wide variety of applications and devices, including thin film deposition, electron beam welding, ion thrusters, electron curing, waste management, and as plasma generators. Electron beam sources include hot filaments and field emission devices. However, these devices are commonly used to produce electron beams in low-pressure applications; at pressures exceeding 10-4 torr, these devices typically begin to operate erratically and ultimately fail, often quickly, due to ion bombardment or exposure to reactive species such as oxygen or fluorine. Cold cathode plasma sources [1], particularly hollow cathodes and RF sources, are favorable at high pressures because of their high current outputs and long lifetimes. The discharge plasma generated in these types of sources supplies the electrons, which are then accelerated to form energetic beams.

NRL has developed a number of hollow cathode electron beam sources capable of producing beams with currents up to a few hundreds of milliamperes and energies up to a few kilovolts for applications ranging from material processing [2] to laboratory investigations of space plasma physics [3]. In many of these, magnetic fields are used to control or confine the electron beams. In Fig. 1, the images of beams injected into magnetic fields of varying geometries were taken during the development of one of these cold cathode sources.

The top image shows a 1-keV electron beam propagating in argon through a cusp field produced at the interface of two opposite polarity solenoidal fields. The cold cathode plasma electron beam source (bright circle) is located within the uniform portion of the first solenoid with the beam velocity aligned with the magnetic field, but the source is not aligned with the axis of the cusp. Near the cusp, the magnetic field diverges radially, and the electrons experience a $qv \times B$ Lorentz force which causes the electron velocity to become somewhat azimuthal. Consequently, the trajectory in the uniform region of the second solenoid is helical. As a result of passing through the cusp, there is a clear radial offset of the gyrocenter from the source location.

The middle and bottom images show 1-keV beams propagating in argon/air mixtures. The beams were injected almost perpendicular to a solenoidal magnetic field. In the middle image, the field is uniform, and the helical trajectory due to the Lorentz force has a constant gyroradius. The bottom image is taken when the solenoidal field is not uniform but rather is configured as a magnetic mirror by increasing the field strength at each end. This is evident in the decreasing gyroradius from the left to the right in the image. Because the field lines are squeezed together where the field strengthens, the field picks up a radial component. An axial component of the Lorentz force therefore opposes the motion of a charged particle into the strong field region. With sufficient perpendicular (gyroscopic) kinetic energy, the motion of such a particle slows and reverses direction, thus "reflecting" at a "mirror" point [4]. The bottom image clearly shows this mirror point: The helical pitch of the electron beam decreases until the trajectory is circular and the beam travels no further. Although more difficult to see, the streak of emission at the top of the helix is probably from electrons reflecting from the mirror point.

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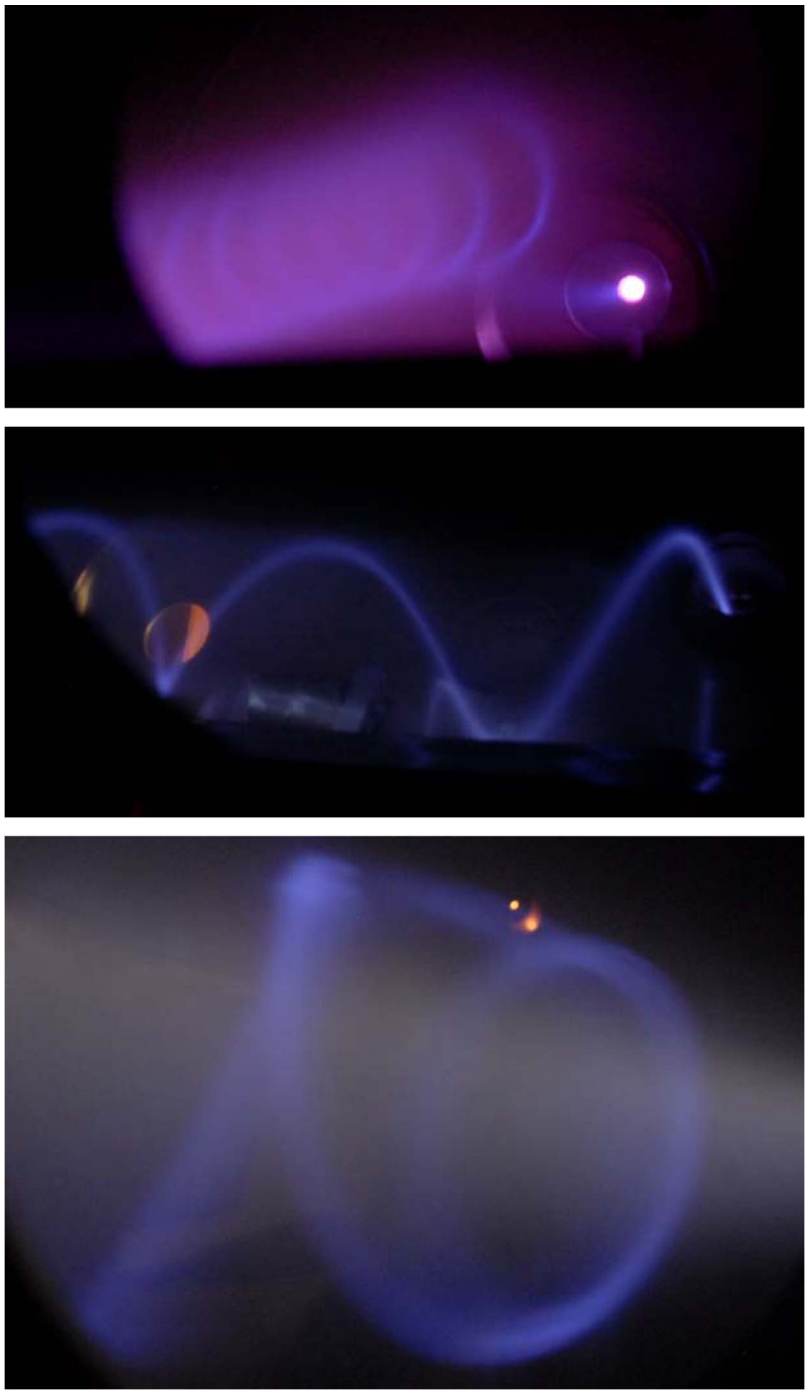

Fig. 1. Electron beam injected (top) through the cusp of adjoining solenoidal magnetic fields, (middle) almost perpendicular to a uniform solenoidal magnetic field, and (bottom) almost perpendicular to a nonuniform solenoidal field containing magnetic mirrors at the ends.